QUANTUM TUNNELLING TRANSDUCER DEVICE

Field of the invention

This invention relates to the accurate measurement and monitoring of fine relative movements or displacements, for example linear or angular separations or translations. The invention has particular utility in the detection of displacements of micro or nano order. Of particular though not exclusive interest is the measurement of vibrations, and quantities derived from positional transduction.

Background Art

There have been a number of published proposals for the use of detectable changes in quantum tunnelling current to measure micro or nano order displacements or motions. For example, Kobayashi et al, have proposed a displacement detector for a micro structure such as an atomic force microscope probe that relies on the extreme sensitivity of a tunnelling current to the length of a gap, in the order of 1nm, between a sample and a sharpened metallic tip. An earlier related disclosure by Kobayashi et al "An integrated tunnelling unit" appears in Proceedings of MEMS 1992, Travemünde (Germany), Feb 4-7, 1992. In an extract entitled "Microsensors get tunnelling" in Design Engineering (Morgan Grampian Ltd, London, U.K.), 1 November 1997, there is a disclosure of an accelerometer that relies on tunnel current effects fabricated in a silicon-on-insulator (S.O.I.) wafer. This device, and a micro-mechanical atomic force sensor head disclosed in European patent publication 262253, rely on the sensitivity of detected quantum tunnelling current to the variable width of a gap, typically between a tip and an opposed surface. That is, the tip and surface move towards and away from each other.

Other disclosures of arrangements utilising quantum tunnelling between a tip and opposed surface are to be found in US patent 4,806,755 and international patent publication WO 97/20189.

The present applicant's prior international patent publication WO 00/14476 discloses micromechanical apparatus for measuring or monitoring the relative position or displacement of two elements in which a pair of elongate electrical conductors are disposed at a mutual separation such that, on application of an electrical potential difference across the conductors, there is a detectable quantum tunnelling current between the conductors. This device is sensitive to the degree of alignment, either lateral or angular, between the opposed conductors. In one form of the device, respective substrates mount opposed arrays of conductors at a spacing in the range 2 to 100 angstroms. Disclosed arrangements for accurately maintaining this gap include the use of C60 nanobearings or a separation film of an organic medium such as cyclohexane.

The concepts and structures disclosed in WO 00/14476 have great promise for a wide variety of applications at micro and nano level. It is an object of the present invention to provide a class of practical devices embodying those concepts.

Summary of the invention

The present invention is essentially directed to a monolithic MEMS or NEMS structure for applying the concepts disclosed in international patent publication WO 00/14476, which structure allows parallel translation of a pair of opposed substrates.

The invention accordingly provides a monolithic micro or nano electromechanical transducer device including:

a pair of substrates respectively mounting one or more elongate electrical conductors; and

resilient solid state hinge means integral with and linking said substrates to relatively locate the substrates so that respective said elongate electrical conductors of the substrates are opposed at a spacing that permits a

detectable quantum tunnelling current between the conductors when a suitable electrical potential difference is applied across the conductors;

wherein said solid state hinge means permits relative parallel translation of said substrates transverse to said elongate electrical conductors.

Preferably, the opposed elongate electrical conductors mounted on the respective substrates are substantially parallel.

Advantageously, said resilient solid state hinge means is dimensioned to have a substantially lower stiffness in a selected direction relative to a direction orthogonal to the selected direction.

In an embodiment, said solid state hinge means comprises at least one outstanding pillar or post from one of said substrates and a web integrally joining the pillar to an edge region of the other substrate. For detecting linear translation, said hinge means would conveniently comprise a pair of solid state hinges, while detection of rotational or angular translation motion would typically require one or four solid state hinges.

In an advantageous device, the respective substrates are typically planar plates or wafers each of substantially uniform thickness and one overlying the other. Rectangular or square plates or wafers are advantageous, although in the case of four angularly spaced solid state hinges, one of the substrates is conveniently of disc form.

Brief description of the drawings

The invention will now be further described, by way of example only, with reference to the accompanying drawings in which:

Figure 1 is an isometric view of a monolithic transducer device according to an embodiment of the invention, having a pair of integral solid state hinges and especially suitable for measuring linear vibrations;

Figures 2 and 3 are respectively a plan view and a side elevational view of the device illustrated in Figure 1;

Figure 4 is a view similar to Figure 1 but from a different angle, of a modified form of the device depicted in Figure 1, having four integral solid state hinges;

Figure 5 depicts a modified form of the device shown in Figure 1 having one hinge so as to be sensitive to rotational translations or vibrations; and

Figure 6 is a similar view of a device having four solid state hinges equally angularly arranged around a disc substrate.

Embodiments of the Invention

The transducer device 10 depicted in Figures 1 to 3 is an integrated monolithic structure typically formed in a material of a type suitable for the manufacture of micro- or nano- structures, for example silicon or gallium arsenide. The device comprises a pair of rectangular plates or wafers 20, 25 , one 20 being larger than the other and forming a base for the structure, and the other 25 being suspended over base plate 20 from a pair of resilient solid state hinge structures 30, 32. In this particular embodiment, each plate or wafer 20, 25 is of uniform thickness, and plate 25 is positioned centrally symmetrically over base plate 20.

Hinge structures 30, 32 are integral with substrate plates 20, 25. Each comprises a wall-like pillar 34 upstanding from base plate 20. In this particular embodiment, each pillar 34 is at an edge of base plate 20, and the outer face 35 of the pillar is flush with the edge face 21 of the base plate, but other arrangements are of course possible. Suspended plate 25 is linked to pillars 34 by respective elongate hinge webs 36, 38 that join opposite sides of plate 25 to the inside face of pillars 34 in mutual coplanar alignment. In this particular configuration, hinge webs 36 are of a width equal to the thickness of plate 25 and arranged so that their upper and lower edges 37 are flush with the respective upper and lower

faces 24 of plate 25 and so that their upper edge 37 is flush with and orthogonally arranged with respect to the upper edge 33 of pillar 34.

It will be understood that because hinge webs 36 are relatively thin in a direction parallel to plates 20, 25 but of relatively large dimension in a direction normal to the plates, the hinges are highly bendable, that is have very low motion resistance, in the parallel direction but are highly stiff and resistant to movement in the normal direction.

The opposed faces 23, 24 of plates 20, 25 are parallel to a high degree of accuracy, and are set at a uniform spacing or gap 50 at which there can be a detectable quantum tunnelling current between opposed conductors in these faces. For utility as a micro- or nano- electromechanical device, these faces 23, 24 have embedded elongate electrical conductors 40 in directly opposed pairs aligned parallel with the plane of hinge webs 36. Suitable electrical contacts 42 are provided on plates 20, 25 for applying an appropriate electrical potential difference across the opposed conductor pairs to give rise to detectable quantum tunnelling current across gap 50. Electrical connections between contacts 42 and conductors 40 can be integrated through the hinge webs 36.

As explained in the aforementioned international patent publication WO 00/14476, this quantum tunnelling current is critically dependent on the spacing between the conductors because the quantum wave function decays exponentially outside the conductor surface, and the detected current will also be a function of any lateral overlap or relative angle between a pair of opposed conductors. The device takes advantage of this linear relationship in that the detected value of the tunnelling current will change as opposed conductors move out of alignment with any relative parallel translational movement of plates 20, 25 transverse to the conductors as the hinge webs 36 bend.

In a particularly suitable application of the transducer device 10 of Figures 1 to 3, linear vibratory motions transverse to the plane of hinges 36 may be detected where the base plate 20 is affixed to a surface and vibration in the surface causes relative vibration of plate 25 on hinge webs 36. A transducer of the illustrated kind

at micro or nano dimensions can function at high frequencies and hence can be used as a sensor of high frequency vibrations, by detecting the peaks in quantum tunnelling current as the opposed conductors oscillate in and out of alignment.

Another application of the transducer device depicted in Figures 1 to 3 is as a flow meter in which plate 25 projects into and responds to the flow. It will be appreciated that the device can be generally applied to the measurement of any quantities derived from positional transduction.

Figures 4 to 6 illustrate further embodiments of monolithic micro or nano devices having alternative characteristics or applications. The structure of Figure 4 is similar to Figure 1 except that it has two hinge webs 130a, 130b; 132a, 132b on either side of the suspended plate 125. This design allows linear motion of the suspended plate 125 with respect to the base plate 120 when the dimensions of the plates are larger than in the case of Figure 1.

Conversely, the structure of Figure 5 has only one web hinge 230 so that the smaller plate 225 projects cantilever fashion from the single post 234. This design allows angular rotation of the cantilevered plate with respect to the base plate. The structure of Figure 6 is also applicable to relative angular rotation of the plates. Here, the suspended plate has four equi-angularly spaced radially extending hinge webs 336 to ensure better, more accurate positioning of the plates and to provide a quite different response.

An exemplary size range for the illustrated structures would involve a suspended plate dimension (edge length or diameter) in the range 100μm to 100nm. Typical hinge dimensions would comprise length 100μm to 100nm, width 50μm to 50nm and thickness 50μm to 10nm.

Any of a variety of known fabrication methods could be employed in the manufacture of the devices of the invention. Appropriate such methods might include:

(1) focussed ion beam (FIB) for interplate gaps 50 of about 15nm or less.

(2) silicon-on-insulator (SOI) for interplate gaps of 5nm or less.

(3) sacrificial removal of gap material using reactive ion etch (RIE).

(4) STM/AFM electrochemical etches.

Another alternative would be to fabricate the two plates separately, eg. by depositing a self-aligned molecular (SAM) layer on the bottom surface, and then welding the two plates to form the hinges, for example by FIB, followed by evaporation of the SAM layer. In this case, the interplate gap would be related to the thickness of SAM material.

For a gap of 1nm or less, presently known fabrication methods would not be suitable. Accordingly, in this case the plates might be fabricated separately and well spaced from one another and an actuator used to bring them into proximity.

The elongate electrical conductors and the contacts could be applied using implantation or nano imprinting technology or any suitable method.

Solid state integrated hinges 40 are very accurate and have very high tolerance. Errors arising from variations in spring constant or web construction details and materials can be controlled and minimised to very low values. The illustrated transducers can function in vacuum, in very aggressive atmospheres, in the presence of strong magnetic and electric fields, in strong radioactive or cosmic radiation, and at exceedingly low or high temperatures.

Reducing the dimensional scale of the transducer devices from the micro to the nano scale in the aforementioned ranges (that is from MEMS to NEMS) should improve performance and reliability of the hinges since, as established by a number of studies, decreasing size is accompanied by a corresponding decrease in the number of defects. Many physical parameters can be controlled to a higher

precision with decreasing size. Such parameters include elastic modulus and several other physical properties, especially for silicon. The reliability of solid state web hinges is very high, with lifetimes estimated to be typically over 10 years or over 300 billion cycles of continuous performance.

Numerical and structural analysis of various alternative constructions, for example using finite element methods, is capable of providing optimised solutions for particular applications. In particular, it is possible to select the geometrical structure of the transducer or of the solid state web hinge, the materials, and dimensions, for the optimal parallel motion of the plate, in a selected motion range and required frequency.

Applications of the devices include force meters, flow meters, gyroscopes, vibration meters and accelerometers. An application of particular interest is to surfaces where minimum disturbance to the environment of the measurement is crucial, for example in measuring aerodynamic surfaces in aeroplane or ship design and testing, or computer disk drive testing.

CLAIMS

1 A monolithic micro or nano electromechanical transducer device including:

a pair of substrates respectively mounting one or more elongate electrical conductors; and

resilient solid state hinge means integral with and linking said substrates to relatively locate the substrates so that respective said elongate electrical conductors of the substrates are opposed at a spacing that permits a detectable quantum tunnelling current between the conductors when a suitable electrical potential difference is applied across the conductors;

wherein said solid state hinge means permits relative parallel translation of said substrates transverse to said elongate electrical conductors.

2 An electromechanical transducer device according to claim 2, wherein the opposed elongate electrical conductors mounted on the respective substrates are substantially parallel.

3 An electromechanical transducer device according to claim 1 or 2, wherein said resilient solid state hinge means is dimensioned to have a substantially lower stiffness in a selected direction relative to a direction orthogonal to the selected direction.

4 An electromechanical transducer device according to claim 1, 2 or 3 wherein said solid state hinge means comprises at least one outstanding pillar or post from one of said substrates and a web integrally joining the pillar to an edge region of the other substrate.

5 An electromechanical transducer device according to any preceding claim wherein, for detecting linear translation, said hinge means comprises a pair of said resilient solid state hinges.

6 An electromechanical transducer device according to claim 5, wherein said hinges include hinges webs in mutual co-planar alignment.

7 An electromechanical transducer device according to any one of claims 1 to 4 wherein, for detection of rotational or angular translation motion, said hinge means comprises one or more angularly spaced solid state hinges.

8 An electromechanical transducer device according to any one of claims 1 to 7, wherein the respective substrates are planar plates or wafers, one overlying the other.

9 An electromechanical transducer device according to claim 8 wherein said plates or wafers are rectangular.

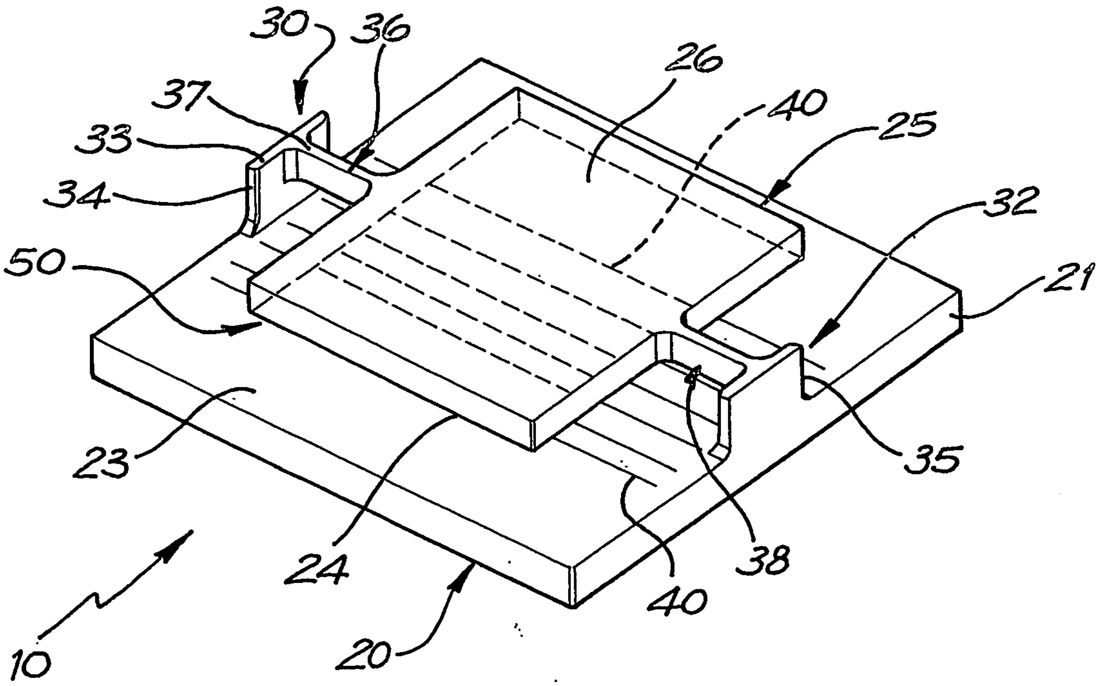
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FIG. 1

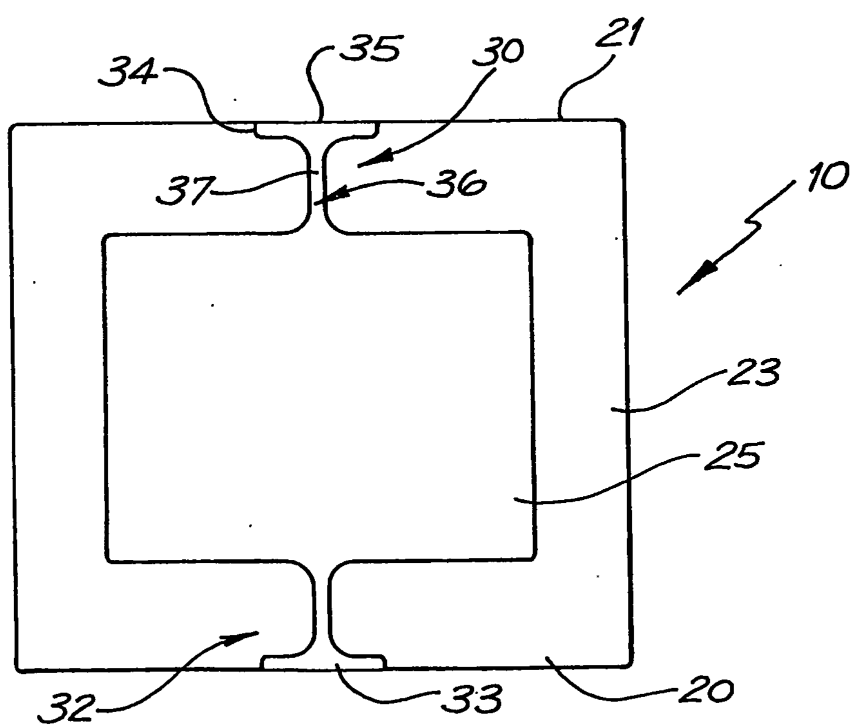
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FIG. 2

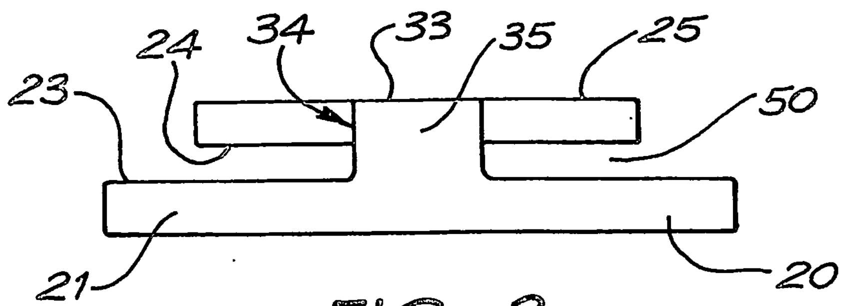

FIG. 3

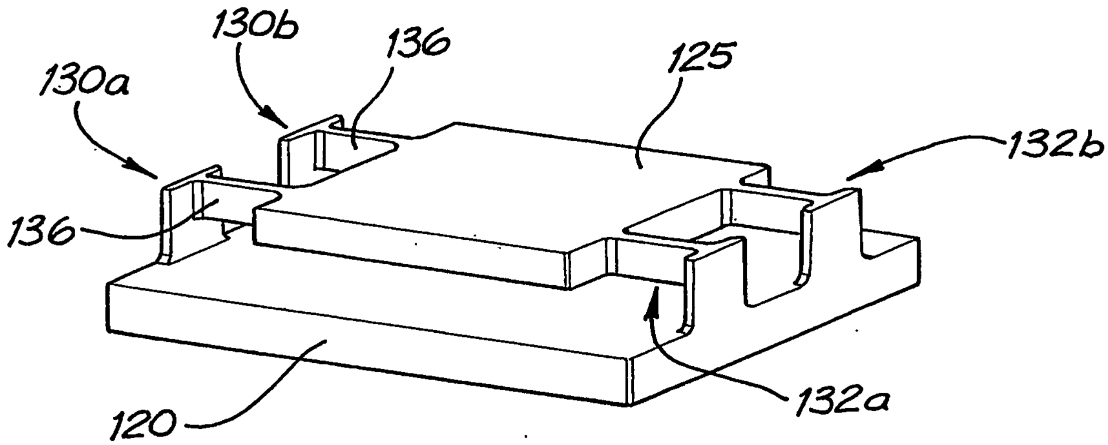

FIG. 4

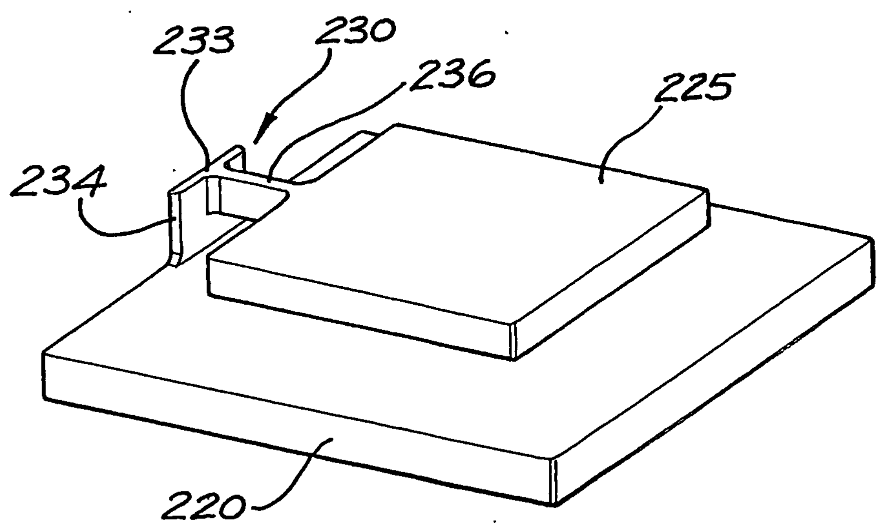

FIG. 5

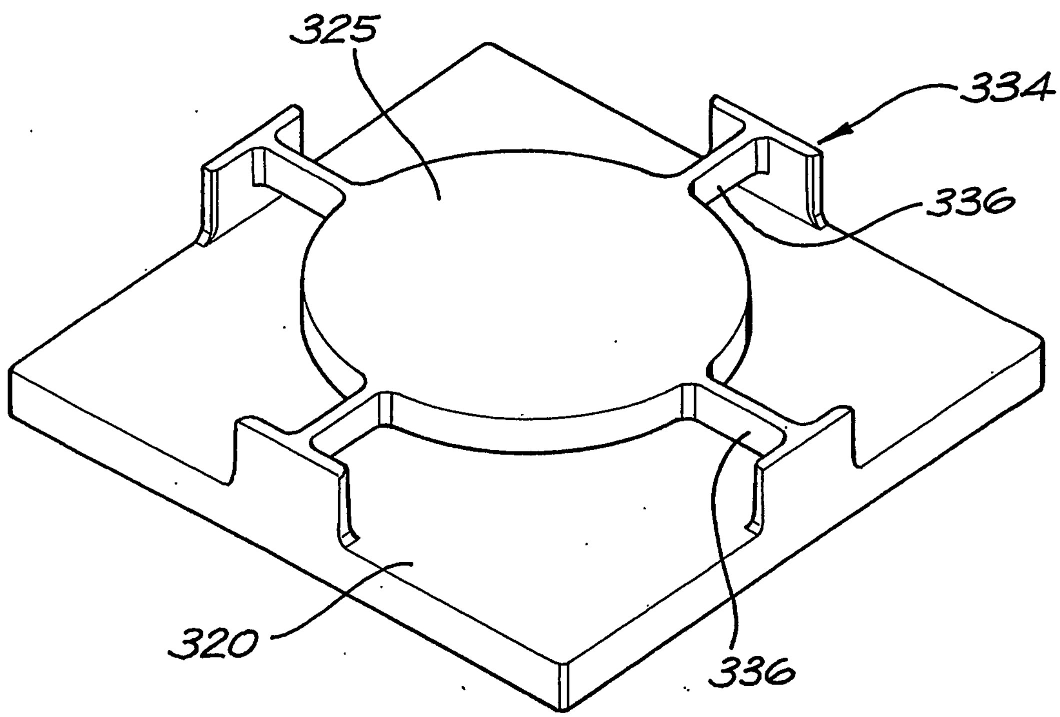

FIG. 6